

Formation and appearance of pulsar-like white dwarfs

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Accretion-driven spin-up of a magnetized white dwarf in a close binary system is discussed. We address a situation in which the magnetic field of the white dwarf is screening during the accretion phase and re-generating due to the field diffusion through the accreted material after it. We find this scenario to be effective for a formation of massive pulsar-like white dwarfs.

Keywords: white dwarf, magnetic field, pulsars, accretion, cataclysmic variables

1. Three basic states of a compact star

A magnetized, rotating compact star can be observed in one of the following three basic states:¹³ *ejector* (spin-powered pulsar), *propeller*, and *accretor*. All of these states are observationally confirmed for neutron stars (see Table 1). The white dwarfs in the accretor state are observed in Cataclysmic Variables (CVs). The low and moderately magnetized white dwarfs (with the surface field $B \leq 1$ MG) in interacting close binary systems usually accrete material from a Keplerian disk while strongly magnetized ($B_* \sim 10 - 1000$ MG) white dwarfs, which are refereed to as Polars, accrete material from an accretion channel.¹⁶ The only white dwarf resembling a spin-powered pulsar is currently identified with the degenerate companion of a peculiar CV AE Aquarii.^{8,9,15}

Table 1. Three basic states of a magnetized, rotating compact star

State	Association	Energy release rate	Observed luminosity
Ejector	Spin-powered Pulsars	$L_{\text{md}} \simeq f_{\text{m}} \frac{\mu^2 \omega_s^4}{c^3}$	$L_{\text{md}} > L_{\text{obs}}$
Propeller	X-ray transients	$L_{\text{pr}} \leq \dot{\mathcal{M}} v_{\text{esc}}^2(r_{\text{m}})$	$L_{\text{md}} < L_{\text{pr}} \leq L_{\text{a}}(r_{\text{m}})$
Accretor	Accretion-powered Pulsars	$L_{\text{a}} \simeq \dot{\mathcal{M}}_{\text{a}} \frac{GM_*}{R_*}$	$L_{\text{sd}} < L_{\text{pr}} < L_{\text{a}}(R_*)$

Note: L_{sd} and L_{pr} are the spin-down power of an Ejector and Propeller, respectively; L_{a} is the accretion power; μ is the dipole magnetic moment, ω_s is the angular velocity, M_* is the mass and R_* is the radius of the compact star; $\dot{\mathcal{M}}$ is the mass capture rate and r_{m} is the radius of the magnetosphere of the compact star; $v_{\text{esc}}(r) = \sqrt{2GM_*/r}$ is the escape velocity at a radius r ; $f_{\text{m}} \sim 1 - 4$ is a dimensionless parameter.¹

2. White dwarfs in the ejector state

Observations show strong magnetization¹⁷ (up to a few $\times 10^9$ G) and fast rotation¹⁴ (up to a period of 30 s) of white dwarfs not to be very unusual. This indicates that

an existence of a strongly magnetized fast rotating white dwarf cannot be excluded. One of these objects (a white dwarf with the spin period of 33 s and the surface field of ~ 50 MG) is discovered in AE Aquarii. The spin-down power of this white dwarf exceeds its bolometric luminosity by a factor of 300 and can be explained in terms of the spin-powered pulsar energy-loss mechanism provided the dipolar magnetic moment of the star is $^7 \sim 10^{34} \text{ G cm}^3$. The fast rotating extended magnetosphere in this case prevents the surrounding material from reaching the stellar surface. The interaction between the surrounding material and the stellar magnetic field leads to a formation of a stream which is flowing out from the binary system.⁸ The spin-down power of the white dwarf is released predominantly in a form of the wind of relativistic particles.^{7,9} Thus, the white dwarfs in the ejector state do exist but how could they form?

3. Accretion-driven spin-up

As the surface temperature of the white dwarf in AE Aquarii is limited to⁶ $T_{\text{av}} \leq 16\,000 \text{ K}$ its age¹² $t_{\text{cool}} > 10^8 \text{ yr}$ turns out to be significantly larger than the spin-down timescale⁵ $t_{\text{sd}} \leq 2 \times 10^7 \text{ yr}$. This indicates that the ejector white dwarf is a product of the binary evolution which included an epoch of its rapid spin-up caused by intensive accretion. The parameters of the spin-up epoch are the following:⁹

- i) accretion from a Keplerian disk at a rate $\dot{M}_{\text{pe}} \geq 10^{-7} M_{\odot} \text{ yr}^{-1}$ on a timescale of a few million years;
- ii) screening of the magnetic field of the white dwarf by the accreted material by a factor of^{2,3,11} 50–100;
- iii) re-emerging of the magnetic field due to diffusion of the stellar magnetic field through the layer of the accreted material on a timescale $t_{\text{em}} < t_{\text{sd}}$, where $t_{\text{sd}} = P_{\text{s}}/2\dot{P}$ is the spin-down timescale which for the parameters of AE Aquarii is $\sim 2 \text{ Myr}$. For this condition to be satisfied the total mass accreted by the white dwarf during the spin-up epoch should not exceed $\Delta M_{\text{a}} \leq 0.009 M_{\odot}$ and the mass of the white dwarf itself is $M_{\text{wd}} \geq 1.1 M_{\odot}$. This implies that the inclination angle of the binary system is $\leq 54^{\circ}$.

An analysis of this accretion scenario suggests that the more massive the white dwarf is the shorter is the spin period which it can reach at the end of the spin-up epoch. Furthermore, the more massive a white dwarf is the smaller amount of the accreted material is required to spin it up to the shortest possible spin period. The timescale of the magnetic field re-emerging of the white dwarf after the spin-up epoch is⁴ $\propto \Delta M_{\text{a}}^{7/5}$. Therefore, the more massive the white dwarf is the faster its magnetic field is re-generated. This increases a probability for the white dwarf to appear as a star in the ejector state.

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